

THOR - Cloud Thickness from Offbeam Lidar Returns

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1. INTRODUCTION

Conventional wisdom is that lidar pulses quickly fade away after penetrating clouds to an optical thickness of about 2. Beyond this limit, multiple scattering by cloud particles increasingly spreads the distinct pulse into a diffuse halo. Since this halo lies outside the narrow field-of-view of most lidars, they are able to probe only thin clouds and the edges of thick clouds. As a result, much of the Earth's cloud cover remained outside the reach of lidar remote sensing.

However, theoretical studies reveal that a lidar pulse entering a cloud spreads by multiple scattering, creating a bright halo that can be mined for cloud information (e.g., Davis et al. 1999). The studies show that in homogeneous clouds the size of the bright halo is proportional to the geometrical cloud thickness: Photons, undergoing random walks by scattering from cloud droplets, create wider halos in thicker clouds because they travel farther without escaping through cloud base. Such results raise the possibility of using halo observations for retrieval of cloud geometrical thickness, and internal properties.

The theoretical advances (confirmed by laboratory experiments) spurred the simultaneous development of three wide field-of-view lidar systems. The up-looking WAIL (Wide-Angle Imaging Lidar) was developed at Los Alamos National Laboratory for ground-based observations, and, having a wider field-of-view, can image halos in lower clouds than a ground-based THOR (Love et al. 2001). Another system, an *in situ* cloud lidar, was built in Colorado for aircraft flights inside clouds (Evans et al. 2003). The THOR instrument described here took its first ground-based measurements of mid- and high-level clouds at NASA GSFC in April 2001, and THOR's first airborne measurements of boundary layer clouds were collected over Oklahoma in March 2002.

THOR reveals the structure of diffuse halos by collecting time-dependent return signals not only from the immediate vicinity of the spot illuminated by its laser, as most lidars do, but also from seven additional rings around this spot (Figure 1). These observations are used for retrieving the geometrical and optical thickness of optically thick stratiform clouds, as well as the vertical profile of cloud volume extinction coefficient.

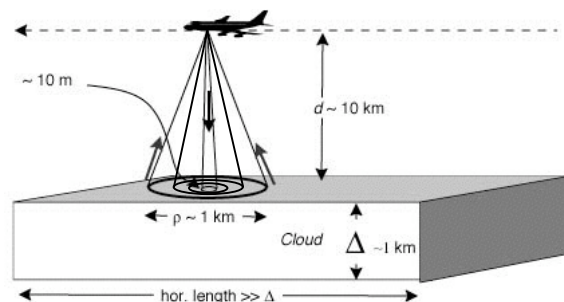


Figure 1. Schematic view of THOR observations.

2. THE INSTRUMENT

2.1 System description

The THOR system's basic structure is illustrated in Figure 2, and its main parameters are listed in Table 1.

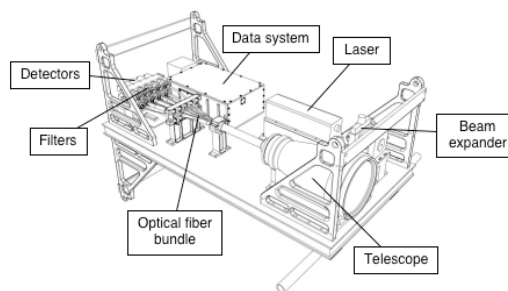


Figure 2. Layout of THOR.

This section discusses THOR's components by following the path of a laser pulse through the system.

When the laser power supply and control unit determines that it is time to emit the next laser pulse, it sends out two simultaneous signals. One signal goes to the data system computer, which then records the pulse's timing and starts archiving the photon counts reported by THOR's detectors. The other signal goes to the laser unit, and causes the solid-state, fiber-coupled Nd:YALO laser to emit a single pulse of green light. The pulse passes through an energy monitor, which determines the pulse energy and reports it to the data system. Next, the pulse is collimated by a 4X beam expander, reducing its divergence to 325 μ rad (full angle). The pulse then leaves the system and travels until scattered by atmospheric particles.

Table 1. Main parameters of the THOR system

Laser	
Pulse rate	1 kHz
Wavelength	540 nm
Pulse duration	8 ns
Pulse energy	max. 225 μ J
Beam divergence	325 μ rad
Receiver	
Telescope lens diameter	19.05 cm
Telescope focal length	23.80 cm
Spectral filter bandwidth	7 nm
Maximum view angle of outermost channels	106.7 mrad (full angle)

Photons returning from the atmosphere are collected by THOR's custom-designed telescope, which creates a 2.5 cm diameter image at its focal plane.

The light forming this image is then collected by THOR's most unique component, a custom-made optical fiber bundle. The bundle consists of approximately 250,000 optical fibers, each 66 cm long, that guide photons from the focal plane to the appropriate detectors. Each fiber has a diameter of about 50 μ m, except for a single 200 μ m fiber that originates at the center of the focal plane. This central fiber captures photons coming from THOR's central field of view—that is, the direct backscatter signal. The remaining fibers are organized into seven concentric annular rings, each collecting photons from a corresponding ring in the focal plane image. Each fiber in a given ring then leads to an associated detector, except for the outermost ring, whose ~150,000 fibers are approximately equally divided among three detectors, that each “see” one of three 120° azimuthal sectors of the outermost annular ring.

This arrangement is necessary, because THOR compensates for the outward weakening of halo signal by doubling the width of each successive fiber ring. This results in each ring collecting light from a four times larger area than its inner neighbor.

Upon leaving the optical fiber bundle, photons pass through spectral filters, each with about 7 nm bandwidth. The filters pass nearly all the returning lidar signal, but block most background illumination. This is crucial, because strong background illumination implies poor signal-to-noise ratio. The current filters are sufficient for nighttime observations, but would pass too much sunlight for effective daytime measurements. As a result, THOR is currently operated only at night.

Photons that pass through the filters are counted by single-photon-counting photo-multiplier-tubes. To keep the data volume manageable, the data system sums up 23 subsequent (0/1) photon detection results in 500 subsequent laser pulses. This reduces THOR's range-resolution to 30.8 m, and its time-resolution to 0.5 s. Considering the NASA P-3B aircraft's cruising speed, this time-resolution corresponds to a spatial resolution of about 77 m.

2.2 Calibration

THOR's calibration involves three separate stages.

First, laboratory experiments establish the relative calibration of the 10 THOR channels. A calibration sphere is attached to THOR's telescope that illuminates the front lens uniformly and isotropically. Since we know how the fields-of-view increase from one channel to the next (successively doubling in radius), we can predict how the photon counts of successive uniformly illuminated channels would increase in an ideal instrument (for most channels, by a factor of 4). The increases observed for the actual instrument are somewhat different from the ideal values. Observing the deviations from ideal increase values allows a relative calibration of THOR channels.

The second stage of calibration is an in-flight check of whether the instrument behavior changed substantially since the last relative calibration. The idea is the same as in the laboratory, but this time the uniform illumination is provided not by a spherical calibration lamp, but by the moonlight reflected from extended cloud fields.

The final, third stage of calibration provides absolute calibration for Channel 1, using the Rayleigh scattering signal returning from clear air. Since relative calibration anchors all channels to Channel 1, Rayleigh scattering can provide an absolute calibration for all THOR channels. Unfortunately, this absolute calibration can be performed only when THOR flies over a thick layer of cloud-free and aerosol-free air.

3. DATA PROCESSING METHODOLOGY

The analysis of THOR data starts with an initial processing that prepares the data for scientific interpretation. This initial processing includes radiometric calibration, removal of background illumination, merger with navigational data coming from the P-3B aircraft, and flagging of data as unsuitable for cloud retrievals whenever the aircraft pitch and roll angle is larger than 3°.

The second step of THOR data analysis estimates the cloud properties by comparing the observations to look-up tables that contain simulated THOR data for a wide variety of clouds—and by selecting the case whose simulated data are most similar to the observations.

3.1 Look-up table generation

The simulated THOR data were generated using a suitably modified version of the UMBC5 Monte Carlo model that participated in the International Intercomparison of 3-dimensional Radiative Codes (I3RC) (<http://i3rc.gsfc.nasa.gov/>).

The main challenge in creating the look-up tables is to keep the computational time manageable while performing low-noise simulations for a wide range of clouds. The Monte Carlo model uses the method of local estimates, and it reduces the simulation noise by smoothing out the forward peak of scattering phase

function for photons that have already been scattered many times (Barker et al. 2003). In addition, we further reduce the required simulation time by several orders of magnitude by using the same photon paths in simulations of many clouds. The scattering angles are identical for all clouds, while the pathlengths between subsequent scattering events are resized according to each cloud's extinction coefficient profile.

Unfortunately, Monte Carlo simulations are quite slow even with these efficiency enhancement methods. Therefore we perform Monte Carlo simulations for only three values of each independent cloud parameter other than geometrical thickness, and we use multidimensional cubic interpolation to fill the entire high-resolution look-up-tables.

Our current computational resources allow us to vary up to seven cloud parameters. Our strategy has been to start by generating look-up tables for simple idealized clouds that can be described by only a few parameters, and then to proceed to more and more complex cloud structures. Our current cloud models have vertical extinction coefficient profiles consisting of linear segments (Figure 3). The cloud retrievals consider all available look-up tables.

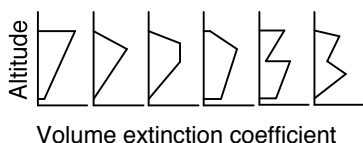


Figure 3. Illustration of some cloud models used in creating THOR look-up tables.

3.4 Estimation of cloud properties

A sample THOR observation used for cloud retrievals is illustrated in Figure 4. The figure shows that THOR's central channel observes intense direct backscatter from near the cloud top, while the outer channels observe a fainter halo formed by multiple scattering deep inside the cloud. The signal of outer channels is delayed because photons need time to reach the halo's outer portions, and it is stretched because some photons meander more while others follow more straight paths.

To maintain maximum flexibility, the retrievals treat the spatial aspect and time-dependence of THOR observations separately. The spatial aspect is characterized through each channel's contribution to the overall detected photon count. The time-dependence is characterized through the width of time (i.e., range) intervals that contain certain percentiles of the time-integrated return signal of each channel.

In practice, retrievals focus on the time-dependence of signals, because this does not require accurate calibration, and on the outer channels and on the tails of time distributions, where cloud thickness has the largest influence.

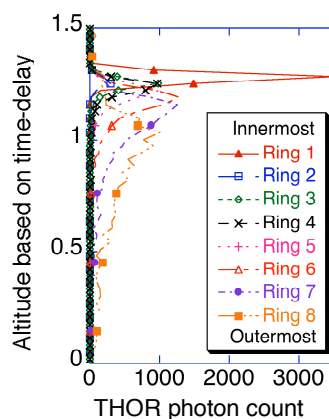


Figure 4. A sample THOR observation collected during the THOR validation campaign described in Section 4.

This has the added benefit of reducing the errors arising from uncertainties in cloud droplet size, as multiple scattering washes out the influence of details in the scattering phase function by the time photons reach the outer rings. On the other hand, focusing on the outer channels and on the tails can create difficulties if the observational noise is large or if the surface reflection can be mixed up with reflection from the lower portions of a cloud. Thus retrieval parameters (e.g., the weight of each channel and percentile bin) must be selected by considering several factors such as the spot size observed by each channel (determined by THOR's altitude above the cloud top), calibration accuracy, noise level (governed by the intensity of background illumination), and surface reflection (influenced by cloud altitude and surface albedo).

4. THOR VALIDATION CAMPAIGN

THOR's first airborne cloud observations took place during the March 2002 THOR validation campaign. During this campaign the NASA P-3B aircraft made repeated passes over the Department of Energy (DOE) Atmospheric Radiation Measurement (ARM) program's Southern Great Plain (SGP) site in central Oklahoma. This site was chosen because of its rich collection of ground-based instruments that provided a wealth of information for validating THOR's cloud thickness retrievals. (See <http://www.arm.gov/>) The idea was to compare THOR's halo-based cloud thickness estimates with thickness values that were obtained as the difference between the cloud top altitude measured by THOR and the cloud base altitude obtained by use of ground based instruments.

The campaign's first three flights took place on the nights of March 19, 20, and 24, respectively. These flights were dedicated to testing the instrument behavior during THOR's first airborne operations and to collecting clear-sky data. The campaign's main science flight took place on March 25, 2002. During the 5 hour long flight, the vicinity of the ARM SGP site was covered by two distinctive cloud layers.

First, a low-level stratus cloud covered the sky completely, thus providing an excellent target for THOR's halo-based retrievals. The cloud base varied from 200 to 500 m above the ground (see below), and the cloud thickness ranged from 500 to 1000 m. Figure 6 shows that the ARM Micropulse Lidar (MPL) clearly detected the cloud base, though it could not provide information on the clouds' inside and top, as cloud droplets quickly scattered the MPL's laser pulses outside its field-of-view.

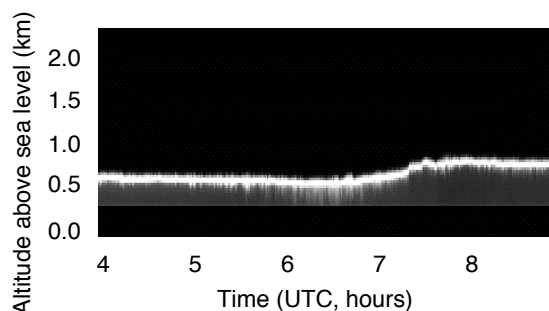


Figure 6. ARM MPL data during THOR's flight.

The second cloud layer was a Cirrus approximately 5.5 km above the ground. Although this cloud was optically too thin to produce a significant halo, it complicated the retrievals for the low-level stratus cloud: It scattered parts of the well-focused downwelling laser pulses into a wider cone, and this widened the halo observed at the low cloud. Thus in order to correctly interpret the halo observations, cloud retrievals need to properly account for the Cirrus spreading effect. Although flying below the Cirrus can certainly help, low-altitude observations pose different challenges: THOR's fixed viewing angles imply that if it flies at lower altitudes, THOR observes smaller areas of a given cloud top, and even its outermost channels see only the relatively inner portions of the bright halo. In order to provide observations from a variety of conditions, THOR made passes over the ARM site at several altitudes.

In addition to the ARM data, we also made use of near-surface temperatures and dew point temperatures at five Oklahoma Mesonet sites that were closest to our flight track. This data was used to estimate the cloud base height via the calculated lifting condensation level. The data revealed significant cloud base variations along the flight track, with a maximum change of up to 350 m from East to West. Thus the cloud base values obtained for the central facility and for these five locations were supplied to a 2D interpolation scheme, which estimated the cloud base at THOR's constantly changing location.

Naturally, the estimated cloud bases are most accurate when THOR flew near the central facility: the uncertainties range from about 20 m within 4 km of the central facility to about 50 m at 30-40 km away. Initial retrievals for a few flight segments (where the Cirrus cloud was thin) showed that THOR cloud thickness retrievals were within the range of uncertainties.

Detailed retrieval results are presented at the conference and in Cahalan et al. (2004).

4. CONCLUSIONS

This paper described the new airborne lidar instrument called THOR, outlined the methodology of its cloud retrievals, and briefly discussed the March 2002 THOR Validation Campaign.

THOR was built to probe clouds that have optical thicknesses larger than 2. The inside of these clouds is beyond the reach of conventional lidar, because cloud particles scatter the distinct laser pulses into a diffuse halo that lies outside the narrow field of view of conventional lidar. THOR's multiple wide fields-of-view allow detailed observations of the reflected halo from aircraft flying several kilometers above clouds. Currently, the primary use of halo observations is retrieving the geometrical thickness of optically thick stratiform cloud layers, although the retrievals simultaneously estimate cloud optical thickness and vertical cloud extinction profile.

Future developments are expected in several areas, including further testing and development of cloud retrievals, exploring the possibility of microphysical retrievals, and an expansion of THOR's capabilities to daytime operations and to measurements of the thickness of snow and sea ice. For more information on THOR, see Cahalan et al. (2004).

5. ACKNOWLEDGMENTS

THOR has been funded by the Goddard Director's Discretionary Fund and the NASA Radiation Sciences Program. We are grateful to Anthony Davis for fruitful discussions, to Luis Ramos-Izquierdo for designing THOR's telescope, to all engineers who helped building THOR, and to all who contributed to the success of the 2002 THOR validation campaign.

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